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DEVELOPMENT OF SOLAR-PANEL SYSTEM FOR THERMALLY ANNEALING RADIATION DAMAGED SOLAR CELLS

FINAL REPORT
CONTRACT NAS5-10445

DECEMBER 1968

PREPARED FOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

THE BOEING COMPANY
AEROSPACE SYSTEMS DIVISION
SEATTLE, WASHINGTON

FINAL REPORT

for

DEVELOPMENT OF SOLAR PANEL SYSTEM FOR THERMALLY ANNEALING RADIATION DAMAGED SOLAR CELLS

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Goddard Space Flight Center

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ABSTRACT

The initial objective of Contract NAS5-10445 was to design and build two operable 1-sq-ft solar-cell panels capable of withstanding 10 thermal-annealing cycles from 20 to 450°C. The panels required a heating system and a means of switching the solar cells from their operating state to the annealing state, and vice versa.

The work accomplished on this contract included: (1) development of a thermal-diffusion bonding process for attaching silver-mesh interconnectors to solderless, silver-titanium-contact silicon solar cells; (2) evaluation of possible heating methods by thermal analysis; and (3) the design and fabrication of a 1-sq-ft high-temperature solar-cell panel.

Thermal-diffusion bonding was used to join silver interconnectors to solar cells without degrading the performance of the solar cells. The bonds withstand over 600 grams in shear and peel loading before failure. Thermal shock to liquid-nitrogen temperature does not degrade the electrical or mechanical integrity of the joint. Photomicrographs of bonds show a diffusion of the silver interconnector into the silver contact of the solar cell. This bond withstands the required 450°C temperature and the bonding process may be useful in other solar-cell applications.

The thermal analysis included investigation of greenhouse heating, electrical heating, and a combination of the two for achieving a 450°C panel temperature. Also evaluated was a black-mirror coated shield for absorbing solar energy and reradiating it to the solar panel. Greenhouse heating supplemented with 100 watts of electrical heat can bring the panel to 450°C in 20 minutes. A black-mirror coated shield can heat the panel to 450°C in 1 hour with no supplementary electrical heat. The black-mirror approach was selected as the method for heating the solar panel.

The delivered solar-cell panel consists of a fiberglass cloth substrate in a Kovar frame with Engelhard CA9R adhesive bonding the solar cells to the fiberglass. The black-mirror shield and back-side thermal shield are stowed on rollers. A 400-Hz motor pulls the shields over the panel for thermal annealing of radiation damage.

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INTRODUCTION

As solar cells become damaged from space radiation their power output decreases. Today, solar-cell panels are designed oversized to provide adequate output power at the end of the mission. However, with the new large solar panels, such as the 5,000-sq-ft Large Area Solar Array (LASA),[1] the added weight and cost of an oversized panel are great enough to justify a search for alternate methods of dealing with radiation degradation. Dr. Fang of NASA-Goddard has shown that solar cells that have become damaged from particulate radiation can be restored to their initial state by thermal annealing.[2] The temperature required for thermal annealing is a function of radiation energy, flux, and annealing time. An upper thermal annealing temperature is 450°C. Until recently, only individual solar cells have been annealed thermally.

A solar-cell panel which can be thermally annealed must be assembled from components that are able to withstand 450°C without failing. A particularly important component is the joint between the interconnector and the contact strip on the solar cell. This report describes the development of a thermal-diffusion process for bonding silver mesh to the solderless silver contact of the solar cell. It also describes the thermal analysis that was used in establishing the best method of heating the panel to 450°C. A description of the test panel is provided.

Outside the scope of this report are tests in which the 1-sq-ft test panel is irradiated and subsequently heated to anneal out the radiation damage. These tests are to be conducted by the National Aeronautics and Space Administration.

TECHNICAL DISCUSSION

This section describes the work accomplished during the contract period. This work will be discussed in the following order:

1) Thermal-diffusion bonding development;

2) Thermal analysis;

3) Test panel design.

THERMAL-DIFFUSION BONDING DEVELOPMENT

The contract required that the solar-cell panel be capable of withstanding 10 cycles of temperature change from 20 to 450°C. The 450°C upper temperature is far above the limits for the soldered solar-cell connections used on conventional panels. Thus, interconnections were identified as an important problem area, and all possible alternates to soldered joints are evaluated.

One of the alternates, thermal-diffusion bonding, was selected as a result of the initial successes obtained in the first quarter. In the first quarterly report,[3] it was shown that silver-mesh solar-cell interconnectors could be bonded to the silver contact of solderless solar cells. By applying the right pressure and temperature, the joints formed were electrically and mechanically sound. A sufficient number of silver-mesh interconnectors were joined to solar cells in vacuum and enough tests were performed to show beyond doubt that thermal-diffusion bonding is satisfactory for meeting the requirements of this contract.

The next paragraphs will describe the performance tests, shear tests, peel tests, temperature cycling tests, and temperature shock tests conducted on thermal-diffusion bonded solar-cell interconnector joints.

Performance Tests

The purpose of the performance tests was to determine solar-cell degradation resulting from the thermal-diffusion bonding process. Degradation in excess of 5% was considered unacceptable.

In this test, 2- by 2-cm n-on-p silicon solderless solar cells supplied by Heliotek were used. The interconnector material was expanded silver mesh (2 Ag 5-6/0) supplied by the Exmet Corporation. The output of the solar cells was measured in xenon light at an intensity of 100 milliwatts per square centimeter. Solar-cell temperature was maintained at 28 ±1°C by keeping the solar cell in contact with a temperature-controlled block.

The performance of 21 solar cells was measured prior to bonding. The solar cells were then placed in the thermal-diffusion bonding tool and a silver-mesh interconnector was thermal-diffusion bonded to the "n" contact of each solar cell. The bonding was done in a vacuum chamber. Each bonded joint was 1.27 cm (0.5 inch) long and 0.051 cm (0.02 inch) wide. After thermal-diffusion bonding, the performance of the solar cells was again measured and compared with the initial performance. The results of this work are shown in Table 1.

The results show that the average change in power after thermal-diffusion bonding is +2.8%. A statistical analysis showed that the average output of the solar cells had indeed increased. There are two possible explanations for this increase in performance: (1) the thermal-diffusion process may decrease the resistance between the silicon and the "n" contact, or (2) the performance of the solar cells may increase merely as a result of heating to 400°C.[4]

The performance curve for Cell 12, which degraded 11.5%, showed an increase in series resistance after thermal-diffusion bonding. The cell broke at the "n" contact when subjected to a solar-cell interconnection shear test, suggesting that microscopic cracks were introduced into the solar cell by excessive pressure during thermal-diffusion bonding.

Table I: EFFECT OF THERMAL-DIFFUSION BONDING ON SOLAR-CELL PERFORMANCE

Cell No.	Current, Short-Circuit Before (mW)	After (mW)	Change (mW)	Volts, Open-Circuit Before (V)	After (V)	Change (V)	Power, Maximum Before (mW)	After (mW)	Change (mW)	(%)
1	115.5	115.5	0	0.532	0.545	+0.013	42.8	43.2	+0.4	+0.9
2	117.5	119.0	+1.5	0.538	0.551	+0.013	44.2	47.3	+3.1	+7.0
3	116.0	118.0	+2.0	0.537	0.553	+0.016	45.2	48.4	+3.2	+7.1
4	116.8	120.0	+3.2	0.530	0.545	+0.015	44.5	47.5	+3.0	+6.7
5	117.5	120.0	+2.5	0.521	0.535	+0.014	44.3	47.7	+3.4	+7.7
6	116.5	116.5	0	0.540	0.545	+0.005	44.2	42.6	-1.6	-3.6
7	116.5	119.0	+2.5	0.536	0.546	+0.010	44.2	47.0	+2.8	+6.3
8	117.0	118.0	+1.0	0.535	0.548	+0.013	45.8	48.0	+2.2	+4.8
9	116.5	118.0	+1.5	0.535	0.541	+0.006	45.6	47.5	+1.9	+4.2
10	116.9	117.5	+0.6	0.539	0.543	+0.004	44.7	44.0	-0.7	-1.6
11	117.5	124.8	+7.3	0.542	0.550	+0.008	45.5	50.0	+4.5	+9.9
12	115.0	116.0	+1.0	0.530	0.535	+0.005	43.6	38.6	-5.0	-11.5
13	116.0	122.0	+6.0	0.541	0.553	+0.012	45.5	49.8	+4.3	+9.4
14	116.2	117.0	+0.8	0.530	0.540	+0.010	44.6	46.5	+1.9	+4.3
15	118.0	117.9	-0.1	0.530	0.545	+0.015	44.7	46.5	+1.8	+4.0
16	116.5	118.5	+2.0	0.539	0.548	+0.009	45.5	46.0	+0.5	+1.1
17	116.5	116.0	-0.5	0.526	0.539	+0.013	44.0	45.8	+1.8	+4.1
18	121.0	120.0	-1.0	0.548	0.545	-0.003	47.7	47.0	-0.7	-1.5
19	117.5	116.8	-0.7	0.543	0.548	+0.005	46.4	46.8	+0.4	+0.9
20	120.0	120.5	+0.5	0.544	0.545	+0.001	47.1	47.9	+0.8	+1.7
21	119.0	118.5	-0.5	0.546	0.545	-0.001	47.6	46.2	-1.4	-2.9

Cells: 2- by 2-cm N/P.

Bond: Bonded on "N" contact only. Bond length ≈ 1.27 cm, width ≈ 0.05 cm.

Interconnector: Expanded silver mesh.

With the exception of Cell 12, which degraded 11.5%, the tests show that thermal-diffusion bonding produces acceptable cell-to-interconnector bonds for this contract.

Shear Tests

To determine the mechanical soundness of the solar-cell interconnector joint, 23 joints were tested in shear with a Unitek Micropull pull-strength tester, Model 6-092-01. The maximum scale reading of the tester was 720 grams. It was arbitrarily decided that the joints should be capable of withstanding at least 500 grams of pull.

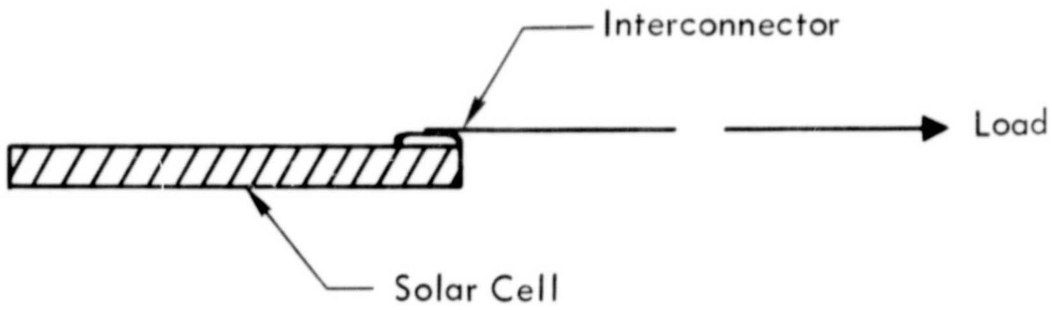
The solar cells used in this test were of the same type as those used in the performance tests. The interconnector material and the method of making the joint were also the same. The solar cells were placed in the testing machine and the shear load was applied, as shown in Figure 1. A head speed of 8.9 cm/min (3.5 in./min) was used. The load at failure was recorded. The results of the shear tests are shown in Table II.

The force required for three of the failures exceeded the scale of the tester, so that the average force at failure was over 610 grams. Three failures occurred at loads below the accepted 500 grams. The modes of these three failures suggested that the pressure during thermal-diffusion bonding was either too high (cell failed) or too low (mesh pulled from contact).

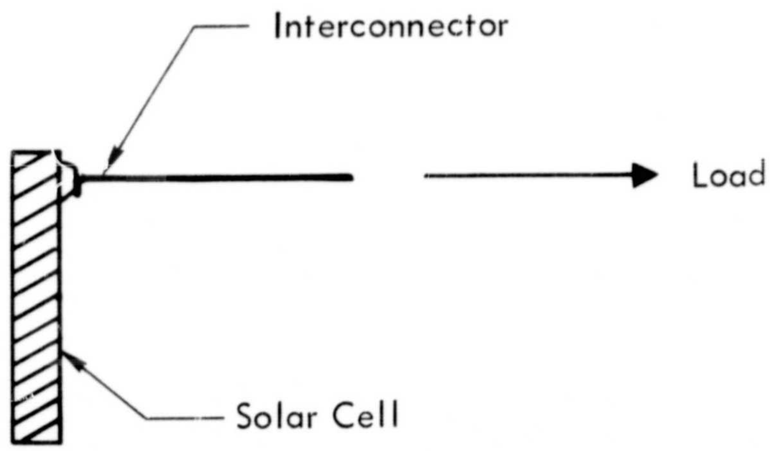
The results show that joints with acceptable mechanical strength can be made if the thermal-diffusion bonding process is properly controlled.

Peel Tests

The solar-cell interconnector joint was subjected to peel tests similar to the shear tests except that the load was applied perpendicular to the solar cells, as shown in Figure 1B. The results of the tests are shown in Table III.



SHEAR TEST
(A)



PEEL TEST
(B)

Figure 1: METHOD OF APPLYING LOAD TO SOLAR CELL — Interconnector Joint in Shear and Peel

Table II: RESULTS OF SHEAR TESTS ON THERMAL-DIFFUSION BONDED SOLAR-CELL JOINTS

Cell No.	Shear Load at Failure (grams)	Mode of Failure
22	540	Mesh failed
23	635	Mesh failed
24	685	Part of mesh pulled from contact
25	675	Mesh failed
26	420	Part of mesh pulled from contact
27	690	Mesh failed
28	705	Mesh failed
29	680	Mesh failed
30	140	Cell failed
31	505	Mesh failed
32	535	Mesh pulled from contact
33	700	Mesh failed
34	300	Mesh pulled from contact
35	720 +	Mesh failed
36	700	Mesh failed
37	700	Mesh failed
38	650	Mesh failed
39	705	Mesh failed
40	690	Mesh failed
41	720 +	Mesh failed
42	720 +	Mesh failed
43	570	Mesh failed
44	650	Mesh failed

+ Load exceeded capacity of test machine

Table III: RESULTS OF PEEL TESTS ON THERMAL-DIFFUSION BONDED SOLAR-CELL JOINTS

Cell No.	Peel Load at Failure (grams)	Mode of Failure
45	670	Mesh failed
46	700	Mesh failed
47	580	Mesh failed
48	420	Mesh pulled from contact
49	400	Mesh pulled from contact
50	600	Mesh failed
51	650	Mesh failed
52	720 +	Mesh failed
53	720 +	Mesh failed
54	720 +	Mesh failed
55	450	Cell failed

+ Load exceeded capacity of test machine

Table IV: RESULTS OF THERMAL CYCLING ON SOLAR CELLS WITH THERMAL-DIFFUSION BONDED INTERCONNECTOR JOINTS

	Current, Short-Circuit			Volts, Open-Circuit			Power, Maximum			
Cell No.	Before Cycling (mA)	After Cycling (mA)	Change (mA)	Before Cycling (V)	After Cycling (V)	Change (V)	Before Cycling (mW)	After Cycling (mW)	Change (mW)	(%)
** 56	120.0	120.0	0	0.535	0.537	+0.002	47.7	46.2	-1.5	-3.2
* 57	118.0	119.0	+1.0	0.548	0.548	0	48.0	47.1	-0.9	-1.9
** 58	118.0	118.0	0	0.541	0.541	0	47.5	46.3	-1.2	-2.6

* 7 cycles from 20°C to 450°C with 100 grams on interconnector.

** 10 cycles from 20°C to 450°C with 100 grams on interconnector.

The interconnector on cell No. 57 broke from rough handling.

The average peel load at failure was more than 600 grams. The mesh usually failed before the joint failed.

Temperature Cycling Tests

The cell interconnector joint was subjected to 10 temperature cycles from 25 to 450°C with a 100-gram weight attached to the cell interconnector.

Silver-mesh interconnectors were thermal-diffusion bonded to three solar cells and the performance of the cells was measured. A 100-gram weight was attached to each interconnector with the solar cells held vertically in a fixture. The fixture with solar cells and weights was placed in an oven preheated to 450°C and allowed to soak for 20 minutes. Then the cells were removed and cooled in front of a fan until the solar cells reached room temperature (25°C). The solar cells were then returned to the oven. This was continued for 10 cycles. After the test, the performance of the solar cells was measured and compared with the initial performance. The results are shown in Table IV.

The test data show that the maximum power decreased as a consequence of the temperature-cycling test. The solar cells were in air when exposed to 450°C and, according to Dr. Fang,* solar cells degrade in air at temperatures above 300°C. This may explain the decrease in performance. The test was not repeated in an inert atmosphere because it showed that the weighted interconnections would not fail at high temperature, and the change in solar-cell performance was within the 5% degradation limit. Since air is a more harsh environment for this test than an inert atmosphere, additional testing in an inert atmosphere should have more favorable results.

Temperature Shock Tests

Five solar cells were temperature-shocked from +100 to -190°C and back to +100°C for 10 cycles, and then subjected to a peel test.

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* Private communication with Dr. P. H. Fang, NASA-Goddard.

Silver-mesh interconnectors were thermal-diffusion bonded to five solar cells, and the performance of the solar cells was measured. These solar cells were then placed in an oven preheated to +100°C, soaked for 2 minutes, then quickly removed from the oven and dropped into liquid nitrogen. The transfer time was 2 to 3 seconds. After a 2-minute soak in liquid nitrogen, the solar cells were put back into the oven. Again, the transfer time was 2 to 3 seconds. After the tenth cycle of this testing, the solar cells were subjected to performance and peel tests.

The test results in Table V show that the electrical and mechanical integrity of the thermal-diffusion bonded joint is not affected by rapid temperature changes from +100 to -190°C.

Table V: RESULTS OF TEMPERATURE SHOCK ON SOLAR CELLS WITH THERMAL-DIFFUSION BONDED INTERCONNECTOR JOINTS

Cell	Max Power Before Test (mA)	Max Power After Test* (mA)	Change (mA)	Change (%)	Peel Load At Failure** (gm)
59	47.7	48.1	+0.4	+0.8	600
60	50.4	50.5	+0.1	+0.2	720+
61	47.9	48.2	+0.3	+0.6	720+
62	47.5	47.5	0	0	680
63	48.4	48.1	-0.3	-0.6	720+

* Thermal-Shock Test
Ten cycles from 100°C to liquid nitrogen
2 minutes at each temperature with a 2- to 3-second transfer time

Mode of Failure
** Mesh failed in all cases
\+ Load exceeded capacity of test machine

Photomicrographs

Four of the solar cells were cross-sectioned perpendicular to the "n" contact, polished, and photographed with an electron microscope. A picture of the cross section of one of the solar-cell/interconnector joints (which is typical of the others) is shown in Figure 2. The fine black line above the "n" contact is the boundary between the contact and the interconnector. A close examination of this line shows where the grains of metal have coalesced across the boundary. This grain growth across the boundary

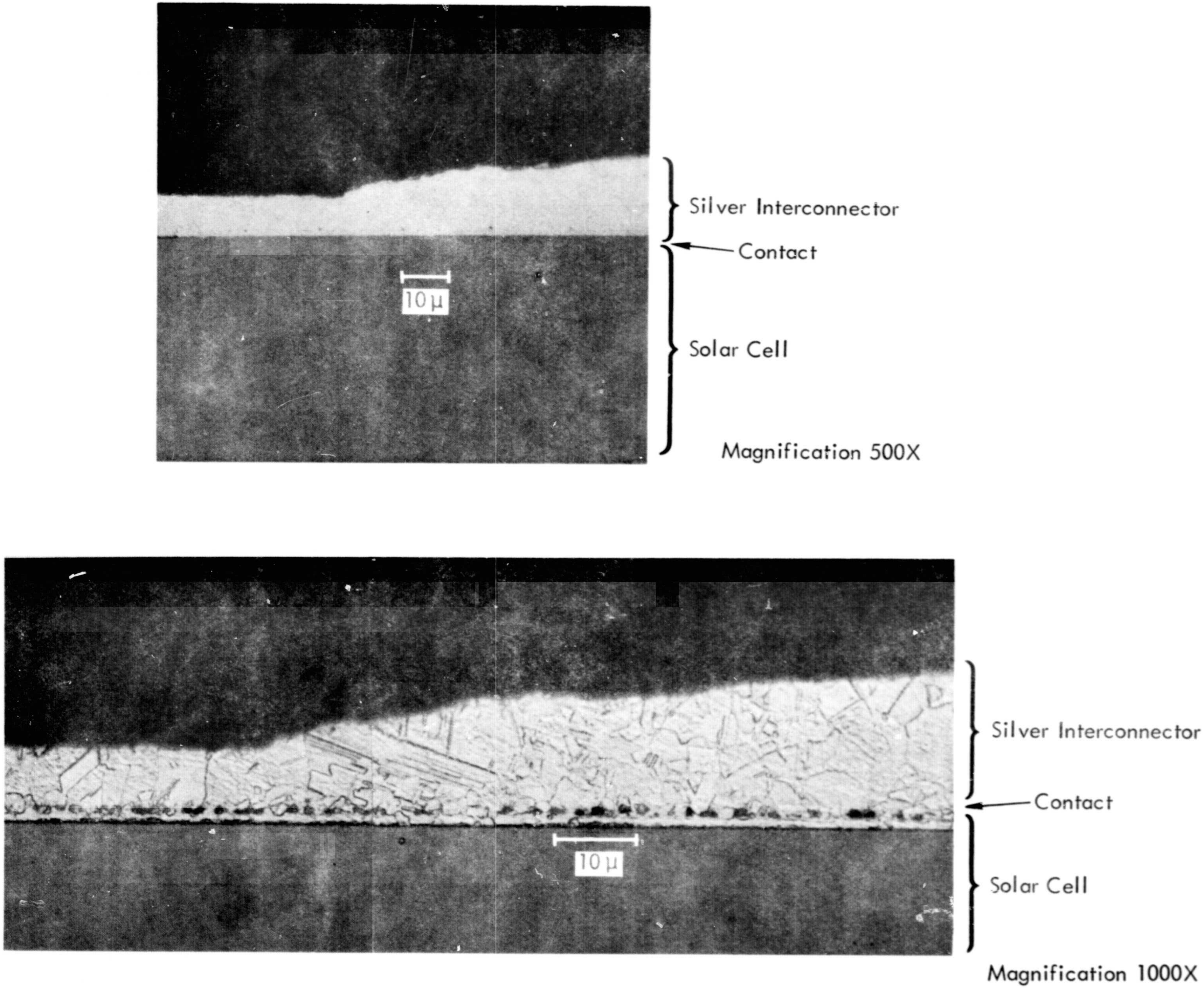


Figure 2: PHOTOMICROGRAPHS OF INTERCONNECTOR TO SOLAR-CELL JOINT

shows that the interconnector and contact are forming into one part, which is the best type of bond that can be expected.

Tool Development

The tests showed that the thermal-diffusion bonded solar-cell interconnector joint meets the requirements of a solar-cell panel capable of withstanding 10 temperature cycles from 20 to 450°C. The next step was to adapt this single-cell process to the assembly of seven-cell parallel groups and to connect the groups into series strings. Seven 1- by 2-cm solar cells needed to be joined in parallel and then joined into a 14-module series string. The panel required four strings.

Thermal-diffusion bonding outside the vacuum chamber was attempted with the thought that scale-up problems would be simplified. The piston that applies pressure to the joint was bored out and a cartridge heater was located inside the piston to get the heat source as close as possible to the joint. A new base to hold the solar cell was made. The pressure of the joint was controlled with weights. Gaseous nitrogen was blown over the solar cell and interconnector to exclude air and thus prevent oxidation.

Due to the convection losses, the heater size had to be tripled over that required in vacuum, and the heating time had to be lengthened to 30 minutes. Good bonds were made with this setup, but because of the problems arising from convection losses and oxidation, thermal-diffusion bonding outside of a vacuum chamber was not used for this contract.

A new tool capable of bonding solar cells into a seven-cell parallel module was built. The tool was calibrated to determine the optimum diffusion-bonding pressure, temperature, and time, using solar cells with integral covers.

The tool (Figure 3) is mounted on the bottom plate of a vacuum chamber. In a bonding operation the solar cells and the silver-mesh interconnector are so located on a base plate that steel wedges will descend on the lines

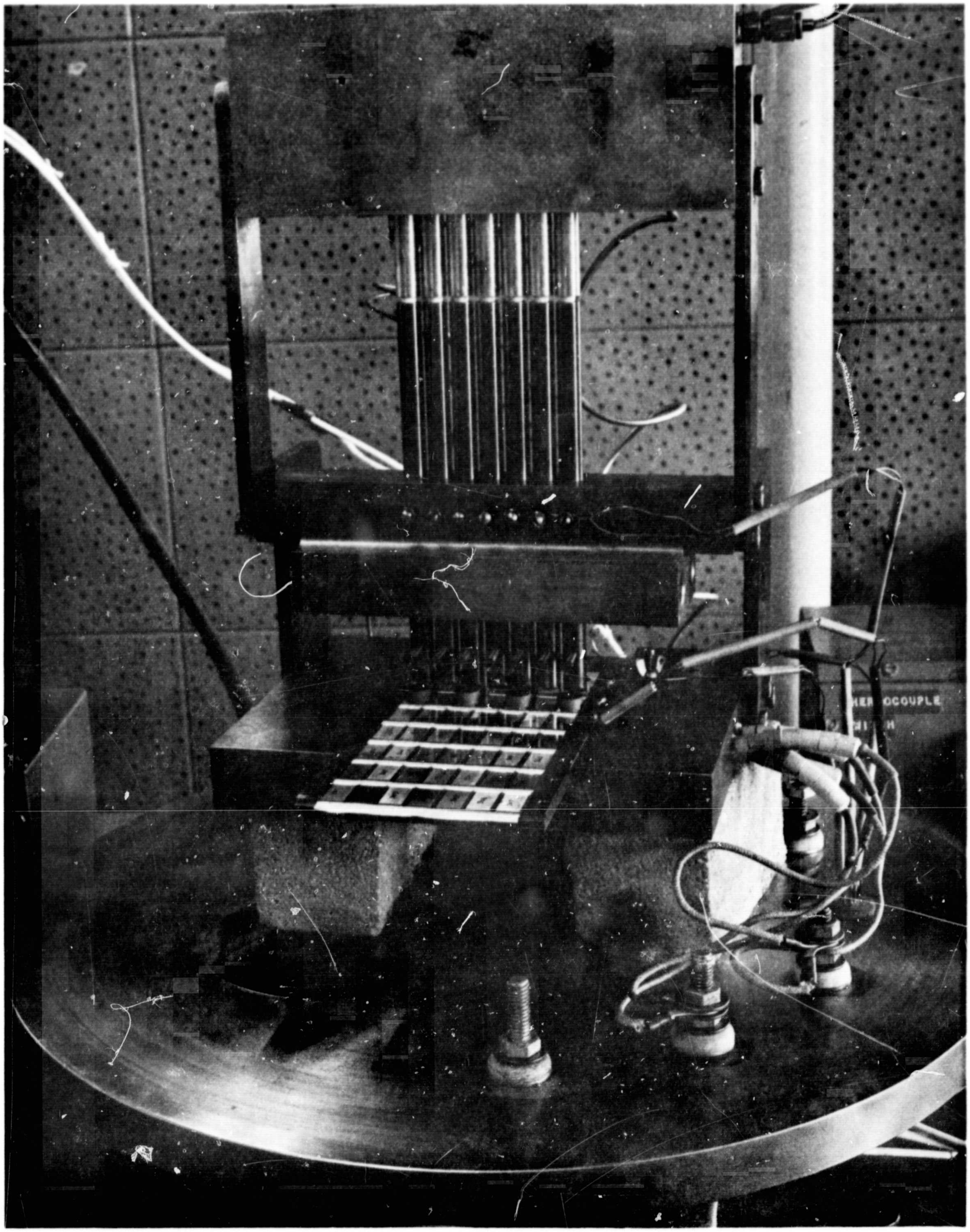


Figure 3: TOOL FOR THERMAL-DIFFUSION BONDING SOLAR-CELL INTERCONNECTORS

CONTRACT NO. NAS5-10445

where the bonds are to be made. Compressed air (60 psi) is then applied to brass pistons that push the steel wedges on the joint. Heaters are inserted into holes in the solar-cell base plate, a bell jar is placed over the tool, and the vacuum chamber is evacuated. The tool is heated to 400°C and allowed to soak for 20 minutes. The heaters are then turned off. After the tool has cooled to 300°C, the chamber is opened, the tool pressure is relieved, and the solar cells are removed.

Fifty solar cells were processed with the new tool to determine the optimum pressure, temperature, and time for making the interconnector joint. The optimum pressure at the bond is 56.2 kg/sq cm (800 psi). Pressures lower than this produced poor bonds; higher pressures have caused the wedges to stick to the silver-mesh interconnector material. Pressures from 10.6 to 212 kg/sq cm (150 to 3,000 psi) were tried.

Temperatures from 290 to 400°C were investigated. Temperatures below 290°C were not satisfactory. It was decided that, because the time to go from 290 to 400°C was small in considering the total time, the 400°C temperature should be adopted in view of all previous work done at 400°C. It was also discovered that if the heaters are turned off as soon as the tool reaches 400°C, the tool cools to 300°C in about 15 minutes, and the resulting joint is poor. A 20-minute soak at 400°C was found to produce a joint acceptable in both mechanical and electrical qualitites.

The tool in Figure 3 was used for making the four 98-cell modules for the 12- by 12-inch solar-cell panel. An auxiliary base plate, visible in Figure 3, was used for bonding interconnectors to the backs of the solar cells.

THERMAL ANALYSIS

To have cool solar cells that are efficient in space, the front surface of the solar cells and the back surface of the panel must have a high thermal emittance. However, high emittance of the panel surfaces is not compatible with heating the panel to 450°C. To heat a 1-sq-ft panel without a shield to 450°C in space would require 2,700 watts.

To reduce the power required for heating, a retractable cover is drawn over the front and back of the panel during annealing. It was first suggested by NASA-Goddard Space Flight Center that the covering on the front of the panel be made from materials such as H-film, which would promote "greenhouse" heating. The four methods Boeing initially investigated for heating the panel in space were (1) greenhouse heating with H-film and coated H-film, (2) greenhouse heating combined with electrical heat, (3) heating only with electrical heat, and (4) heating with a black-mirror absorptive coating.

Greenhouse Heating

The initial thermal analyses of the greenhouse method were based on the back side of the solar-cell array being adiabatic (no heat losses). This assumption is justified on the basis that initial analyses were only feasibility studies of the method. The problem is then one of solar radiosity and infrared radiation on the Sun side of the solar-cell array.

A simple iterative BLITZ (simplified FORTRAN) program was written to solve the radiosity problem in the solar spectrum. This program uses the equations presented in Figure 4 to solve for the solar heat input, Q, to each of the "n" layers of H-film and the solar cells. The optical properties of the H-film and the solar cells are given, as well as the solar flux, S. Solar reflectance is p, solar transmittance is τ and radiosity is J.

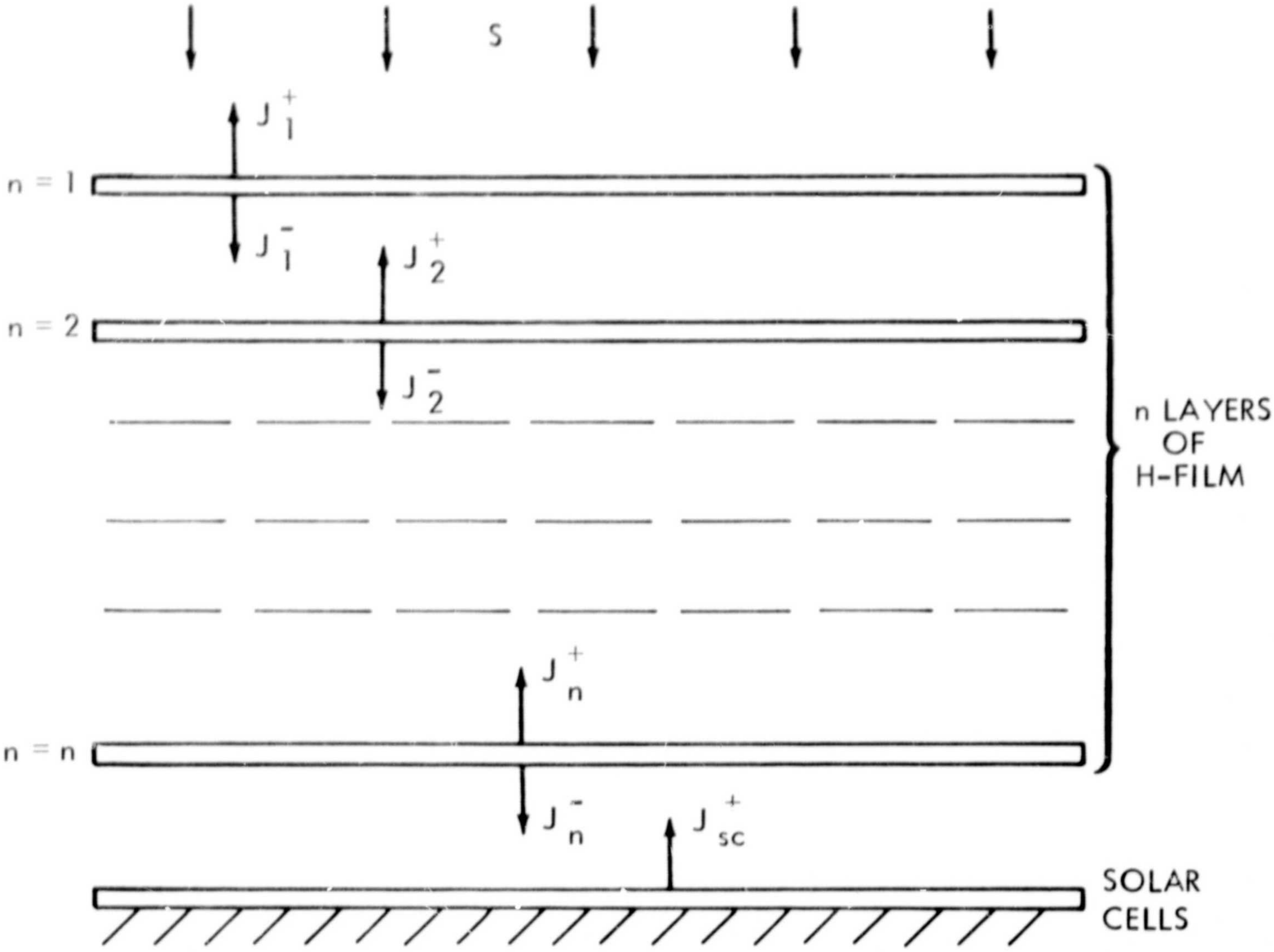
Given the solar heat input, Q, to each of the "n" layers of H-film and the solar-cell array, radiation heat balance equations can be written for each layer and the solar-cell array using the following terms:

$$Q_1 + \sigma \mathcal{F}_F (T_2^4 - T_1^4) = \sigma \varepsilon_F T_1^4$$

$$Q_2 + \sigma \mathcal{F}_F (T_3^4 - T_2^4) = \sigma \mathcal{F}_F (T_2^4 - T_1^4)$$

$$Q_n + \sigma \mathcal{F}_{CF} (T_{SC}^4 - T_n^4) = \sigma \mathcal{F}_F (T_n^4 - T_{n-1}^4)$$

$$Q_{SC} = \sigma \mathcal{F}_{CF} (T_{SC}^4 - T_n^4)$$



$$J_1^+ = \rho_1 S + \tau_1 J_2^+ \qquad J_1^- = \tau_1 S + \rho_1 J_2^+$$

$$J_2^+ = \rho_2 J_1^- + \tau_2 J_3^+ \qquad J_2^- = \tau_2 J_1^- + \rho_2 J_3^+$$

$$J_n^+ = \rho_n J_{n-1}^- + \tau_A J_{sc}^+ \qquad J_n^- = \tau_n J_{n-1}^- + \rho_n J_{sc}^+$$

$$J_{sc}^+ = \rho_{sc} J_n^- \qquad J_{sc}^- = 0$$

$$\left.\begin{aligned} Q_1 &= S + J_2^+ - J_1^+ - J_1^- \\ Q_2 &= J_1^- + J_3^+ - J_2^+ - J_2^- \\ Q_n &= J_{n-1}^- + J_{sc}^+ - J_n^+ - J_n^- \\ Q_{sc} &= J_n^- - J_{sc}^+ \end{aligned}\right\} \text{SOLAR HEAT INPUT}$$

Figure 4: RADIOSITY EQUATIONS

where:

σ = Stephan-Boltzmann constant

$\mathcal{F}_F = \dfrac{\epsilon_F}{2-\epsilon_F}$

ϵ_F = infrared emittance of the H-film ($\epsilon + \rho_{IR} = 1$)

$\mathcal{F}_{CF} = \dfrac{1}{1/\epsilon_F + 1/\epsilon_{CF} - 1}$

ϵ_{CF} = infrared emittance of the solar cells.

These terms can be rearranged and manipulated to give the following equation for the steady-state temperature of the solar-cell array:

$$T_{sc} = \left\{ \frac{Q_{sc}}{\nabla\mathcal{F}_{CF}} + \frac{1}{\nabla\mathcal{F}_F} \left[(n)\ (Q_{sc}) + Q_{TOT} \left(\frac{\mathcal{F}_F}{\epsilon_F} - 1 \right) + \sum_{i=1}^{n} iQ_i \right] \right\}^{1/4}$$

where $$Q_{TOT} = Q_{sc} + \sum_{i=1}^{n} Q_i$$

Initial calculations of the steady-state solar-cell temperatures with assumptions as shown are presented below, assuming a near-Earth solar constant 140 mw/sq cm (442 Btu/hr/sq ft):

Case	n	$(\alpha_s)_{sc}$	$(\tau_s)_F$	$(\rho_s)_F$	$(\alpha_s)_F$	ϵ_{sc}	ϵ_F	T_{sc}(°C)
1	6	0.7	0.841	0.083	0.076	0.85	0.60	372
2	8	0.7	0.841	0.083	0.076	0.85	0.60	396
3	10	0.7	0.841	0.083	0.076	0.85	0.60	412
4	10	0.7	0.349	0.301	0.35	0.85	0.60	201

Cases 1 through 3 were performed initially for optical solar properties thought to be indicative of uncoated H-film (Reference 2). Further analyses of uncoated H-film led to the following properties (solar):

α_s = 0.276

τ_s = 0.635

ρ_s = 0.089

Furthermore, it appears from the limited data available (to 2.7 microns) that uncoated H-film may be highly transparent in the infrared, thus rendering the above analysis incorrect and the feasibility becomes zero.

Case 4 is representative of coated H-film.[2] Here, the H-film indeed appears opaque in the infrared and also appears to exhibit a low emittance. Again, additional spectral data is required before a firm conclusion can be reached. What is desired is a film that is opaque and has a low emittance in the infrared, and yet has high transparency in the solar spectrum.

Additional samples of possible greenhouse materials were sent to Boeing by NASA for anlysis. The following properties were obtained from spectral measurements of H-film and mylar samples having a PE-81-E coating and of a clear teflon film:

H-Film (PE-81-E)	$\alpha_s = 0.42$,	$\tau_s = 0.41$,	$\rho_s = 0.17$,	$\varepsilon_{IR} = 0.28$,	$\rho_{IR} = 0.72$
Mylar (PE-81-E)	$\alpha_s = 0.27$,	$\tau_s = 0.55$,	$\rho_s = 0.18$,	$\varepsilon_{IR} = 0.27$,	$\rho_{IR} = 0.73$
Teflon		$\tau_s = 0.96$,	$\rho_s = 0.04$,	$\varepsilon_{IR} = 0.63$,	$\rho_{IR} = 0.37$

where α_s = total absorptance in the solar spectrum

τ_s = total transmittance in the solar spectrum

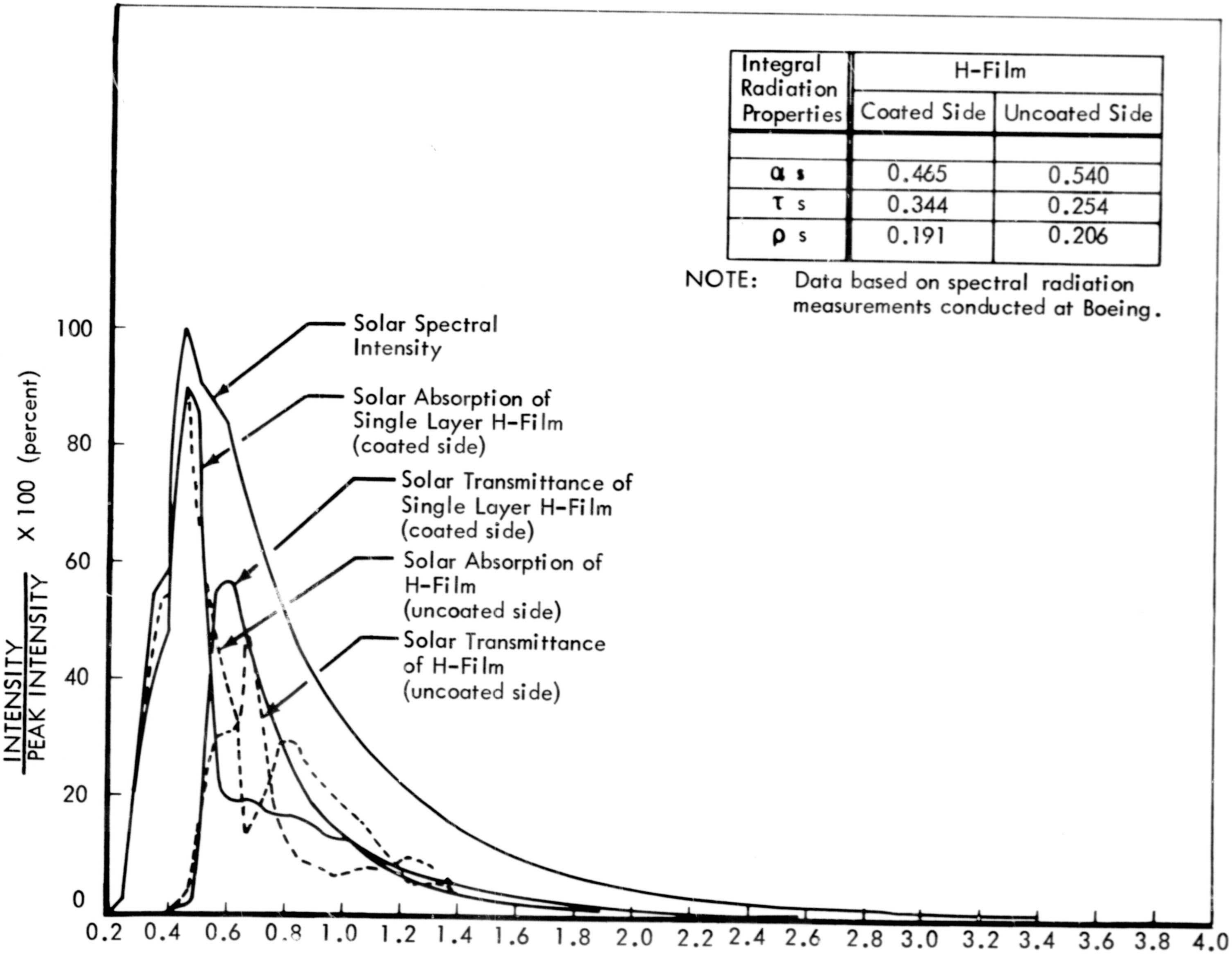
ρ_s = total reflectance in the solar spectrum

ε_{IR} = total emittance in the infrared spectrum

ρ_{IR} = total reflectance in the infrared spectrum

Spectral H-film characteristics are shown in Figure 5. The spectral absorptance and transmittance have been separated to show the values for the coated and uncoated sides of the film.

The time-temperature history of the coated H-film greenhouse system is shown in Figures 6 and 7. Calculations for Figure 6 were based on a 1-sq-ft solar-cell panel with one layer of coated H-film on the front of



Integral Radiation Properties	H-Film	
	Coated Side	Uncoated Side
α_s	0.465	0.540
τ_s	0.344	0.254
ρ_s	0.191	0.206

NOTE: Data based on spectral radiation measurements conducted at Boeing.

Figure 5: SPECTRAL CHARACTERISTICS OF H-FILM WITH PE-81-E COATING

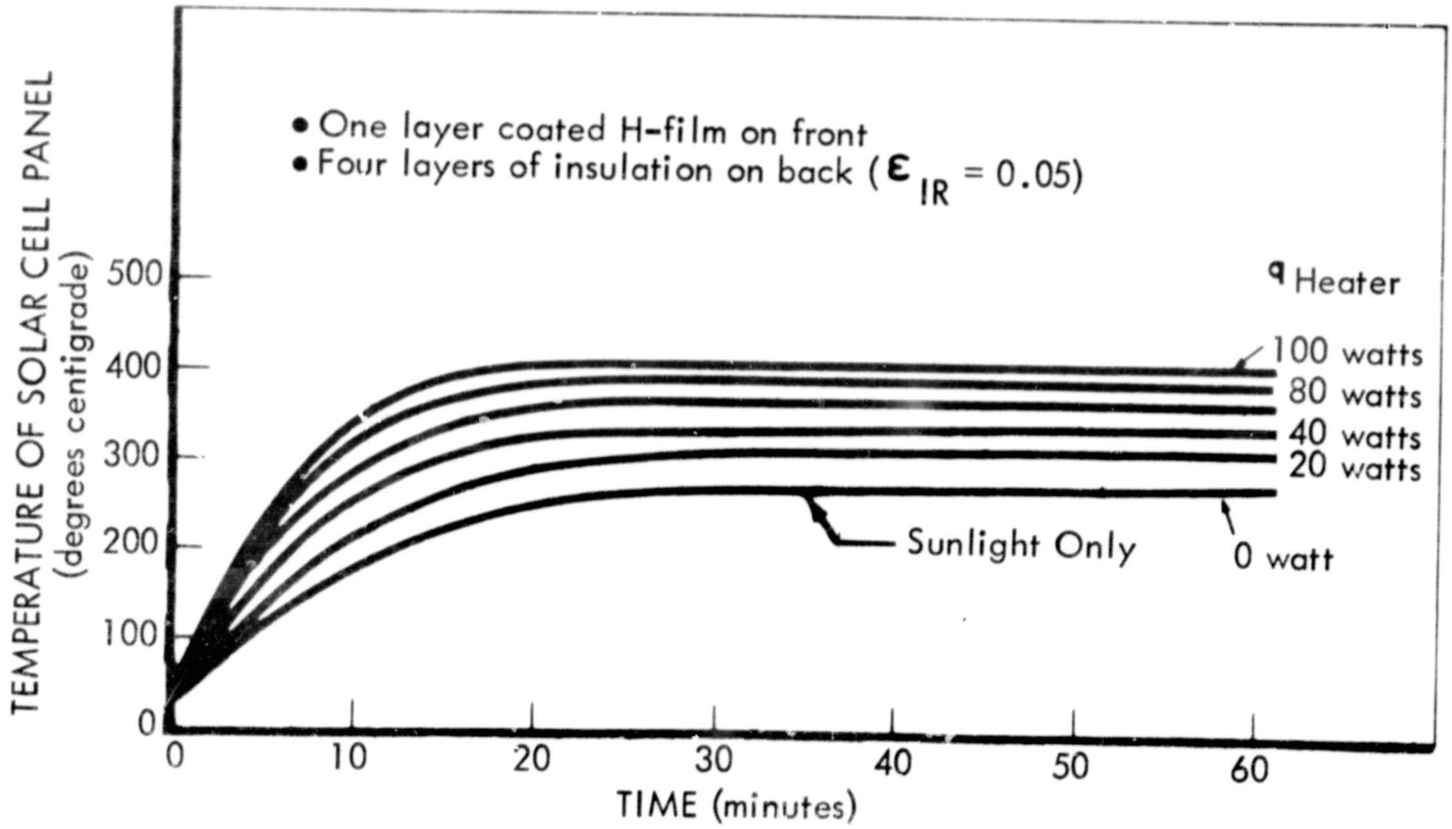


Figure 6: TIME-TEMPERATURE HISTORY FOR PANEL COVERED WITH ONE LAYER OF COATED H-FILM

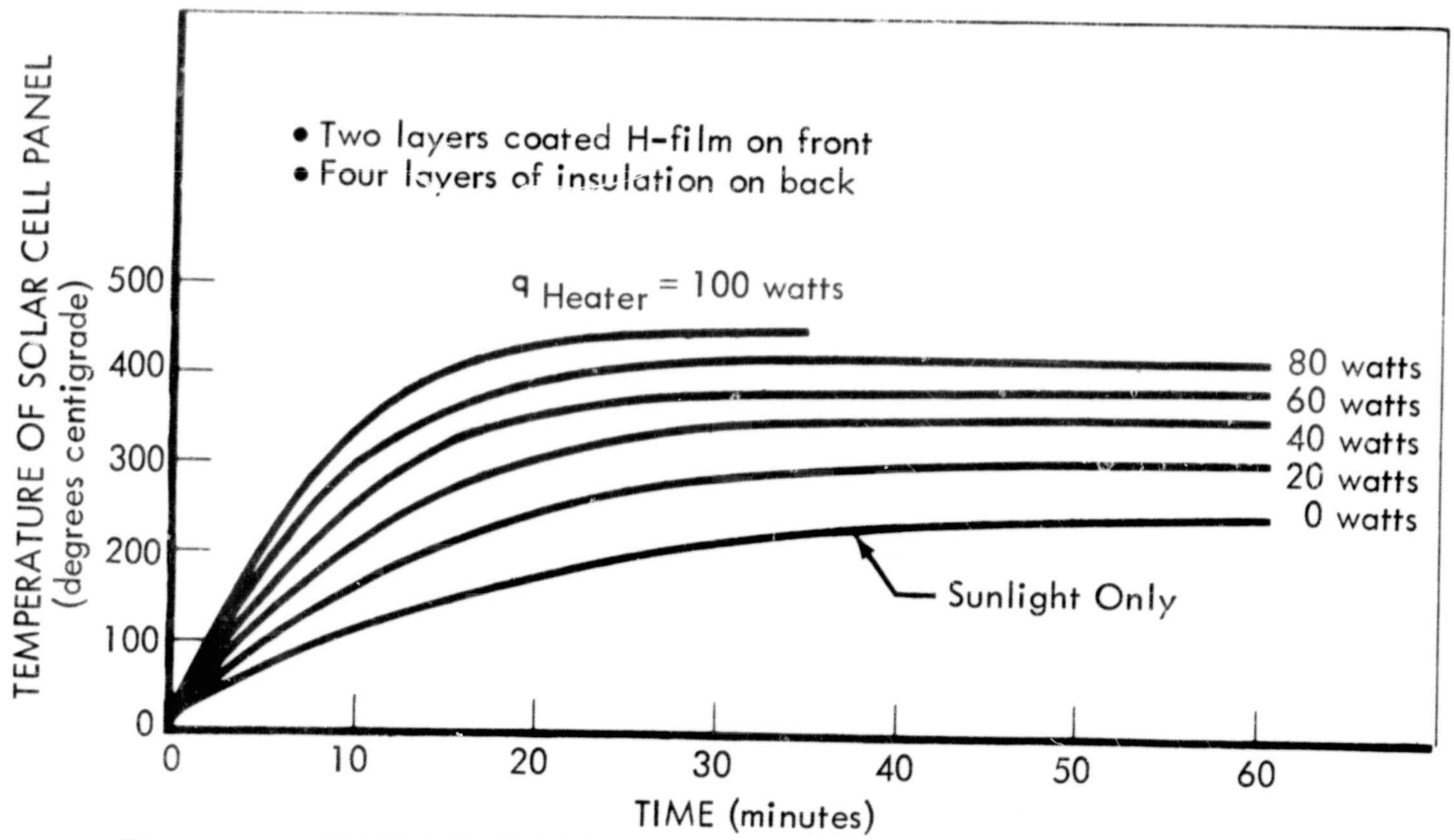


Figure 7: TIME-TEMPERATURE HISTORY FOR PANEL COVERED WITH TWO LAYERS OF COATED H-FILM

the panel and four spaced layers of aluminum insulation on the back of the panel. The H-film coating is PE-81-E, a high-transmission electrically conducting coating, made by Libbey-Owens-Ford Glass Company. For Figure 7, two layers of coated H-film were used on the front of the panel, with all other conditions the same as in Figure 6.

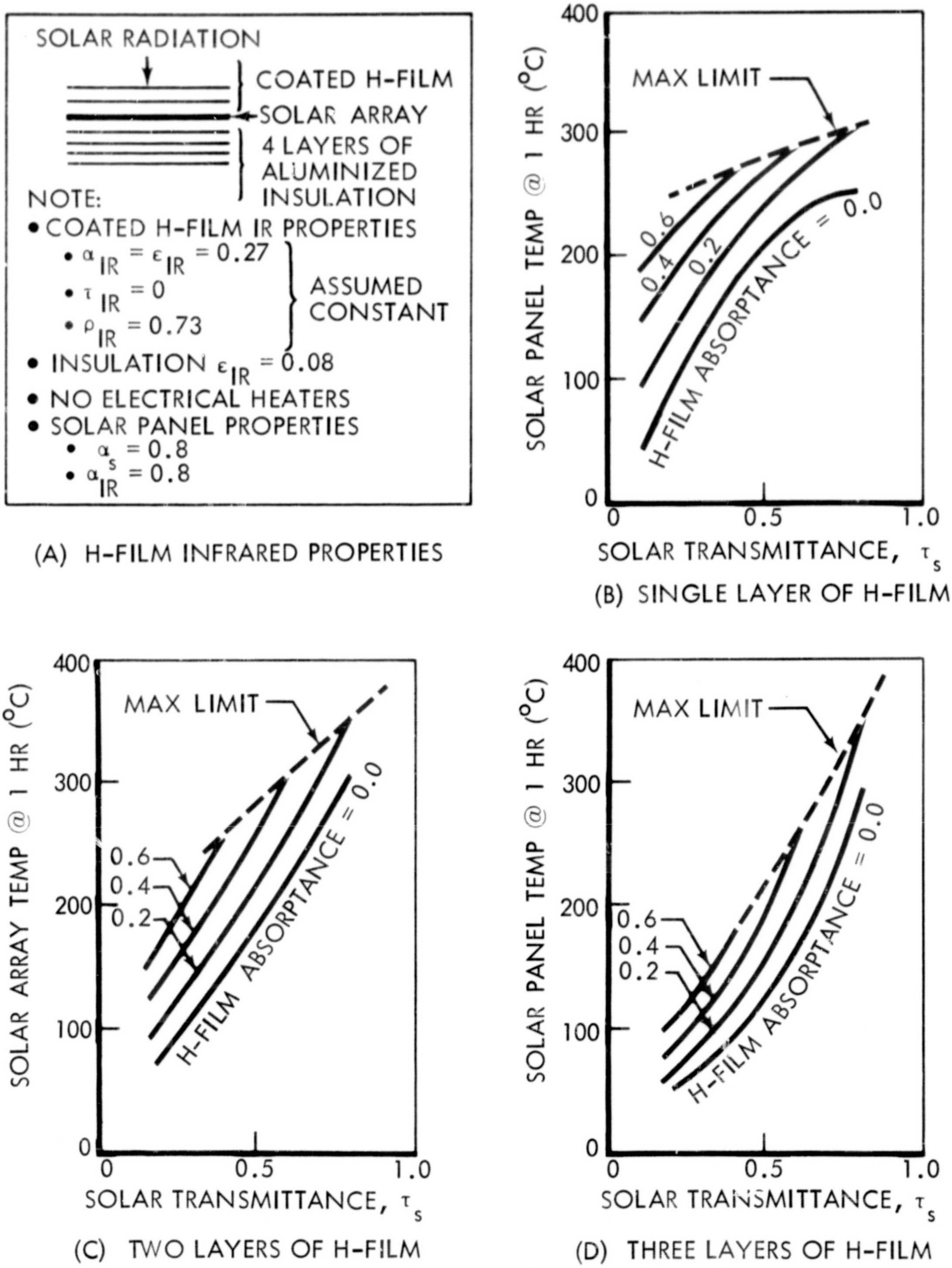
The curves in Figures 6 and 7 show that with only solar radiation, one layer of coated H-film will produce a panel temperature of only 280°C after 1 hour of greenhouse-type heating. Adding a second layer of coated H-film results in a lower temperature of 250°C after 1 hour. These data apply to a 1-sq-ft panel with certain assumed edge and backside losses.

The data show that with no electrical heating, as the number of layers of H-film is increased, the achievable steady-state temperature becomes lower because edge losses increase with the number of layers of H-film. Thus, the analysis was not carried beyond two layers. The lower panel temperature obtained with two layers of H-film results from solar absorption in the second layer of H-film. This absorption becomes less significant when electrical heat is supplied. In fact, the insulating effect of two layers of H-film aids in achieving a 450°C panel temperature.

An additional analysis shows the effect of coated H-film properties on the solar-cell panel temperature after 1 hour of greenhouse heating. The calculations assumed that there were no edge losses. Other assumptions are summarized in Figure 8A. Figures 8B, 8C, and 8D show the panel temperature after 1 hour of solar heating under one, two, and three layers of H-film, respectively. The curves show that multiple layers of H-film with unusual properties would be required before one could expect to achieve a 450°C thermal-annealing temperature. However, greenhouse heating may be practical if thermal annealing could be achieved with temperatures lower than 450°C.

Greenhouse Heating With Electrical Heating

Solar greenhouse heating can be supplemented with electric heat to achieve a 450°C temperature in 1 hour. Figures 6 and 7 show the effect of using



(A) H-FILM INFRARED PROPERTIES

(B) SINGLE LAYER OF H-FILM

(C) TWO LAYERS OF H-FILM

(D) THREE LAYERS OF H-FILM

Figure 8: EFFECT OF H-FILM PROPERTIES ON THE SOLAR PANEL TEMPERATURE AFTER 1 HOUR OF GREENHOUSE HEATING

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electric heaters on the back of the panel structure in addition to sunlight. A value of 100 watts/sq ft was assumed as an arbitrary upper limit for panel power. The achievable steady-state temperature with one layer of coated H-film and 100 watts of power is 410°C. With two layers of coated H-film and 100 watts of power, the panel temperature reaches 450°C in less than 1 hour.

Electrical Heating

With four layers of aluminum foil on the front side, four layers on the back, and no solar heat, the 450°C annealing temperature can be reached in 1 hour with 50 watts of electrical heating power.

The effect of the number of heat radiation shields on heat leakage at 450°C is shown in Figure 9. These data show that the optimum number of heat radiation shields is two to four layers using a density of 60 layers per inch. As shielding density decreases, heat leakage increases for a given number of layers of shielding because heat is lost through the edges of the shielding. Using four layers of insulation at a density of 60 layers per inch, the time-temperature profile becomes as shown in Figure 10, which indicates that 50 watts of heat will bring the 1-sq-ft panel to 450°C in 1 hour.

Black-Mirror Absorptive Heating

An alternate approach, suggested by Dr. Fang, is to use a black-mirror coating. This coating has high absorptance in the solar spectrum and low emittance in the infrared. Two samples of this material sent to Boeing by Dr. Fang have the following properties:

Sample	Absorptance	Emittance
1	0.895	0.15
2	0.863	0.07

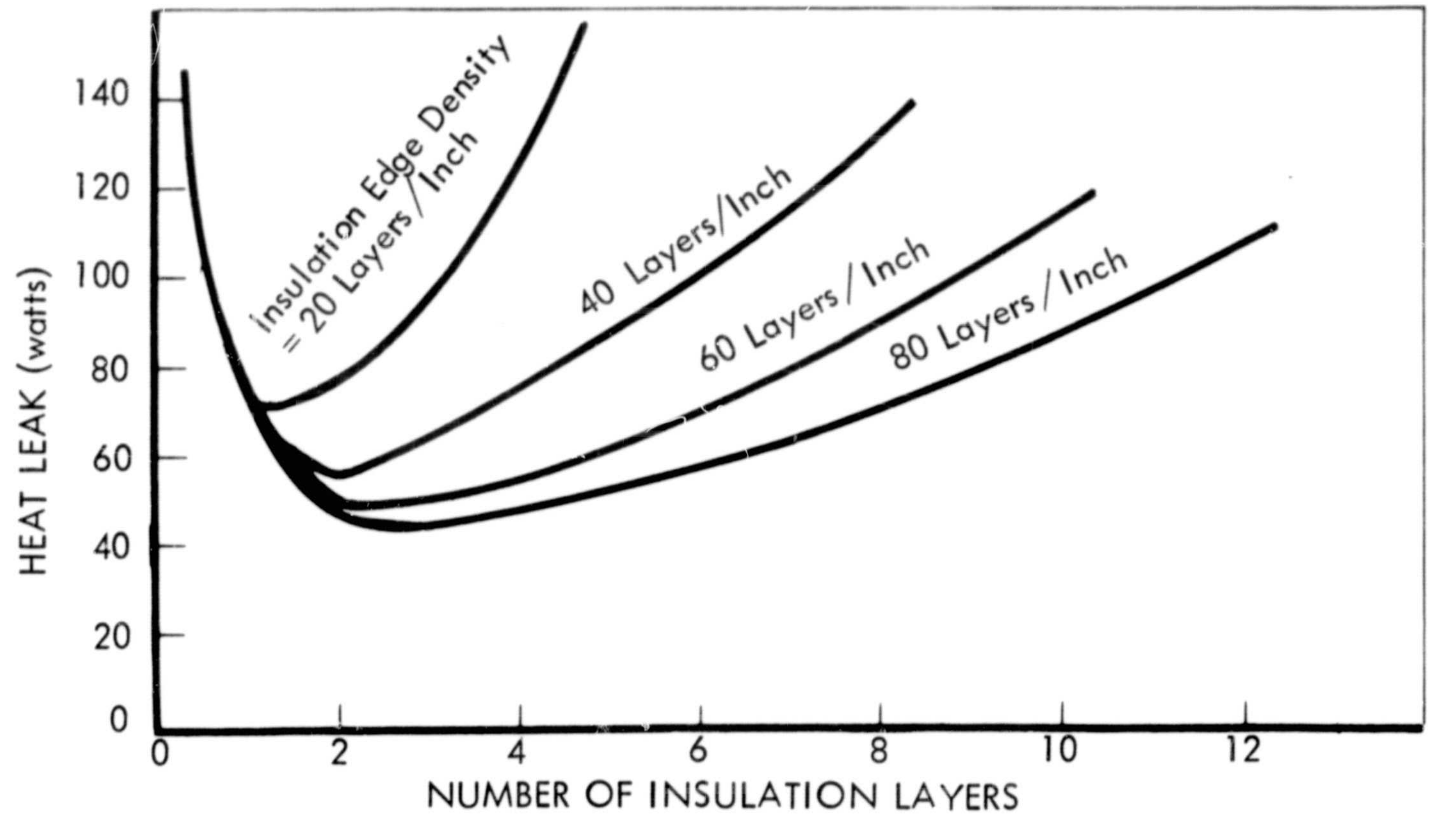

Figure 9: EFFECT OF NUMBER OF ALUMINUM INSULATION LAYERS ON HEAT LEAKAGE

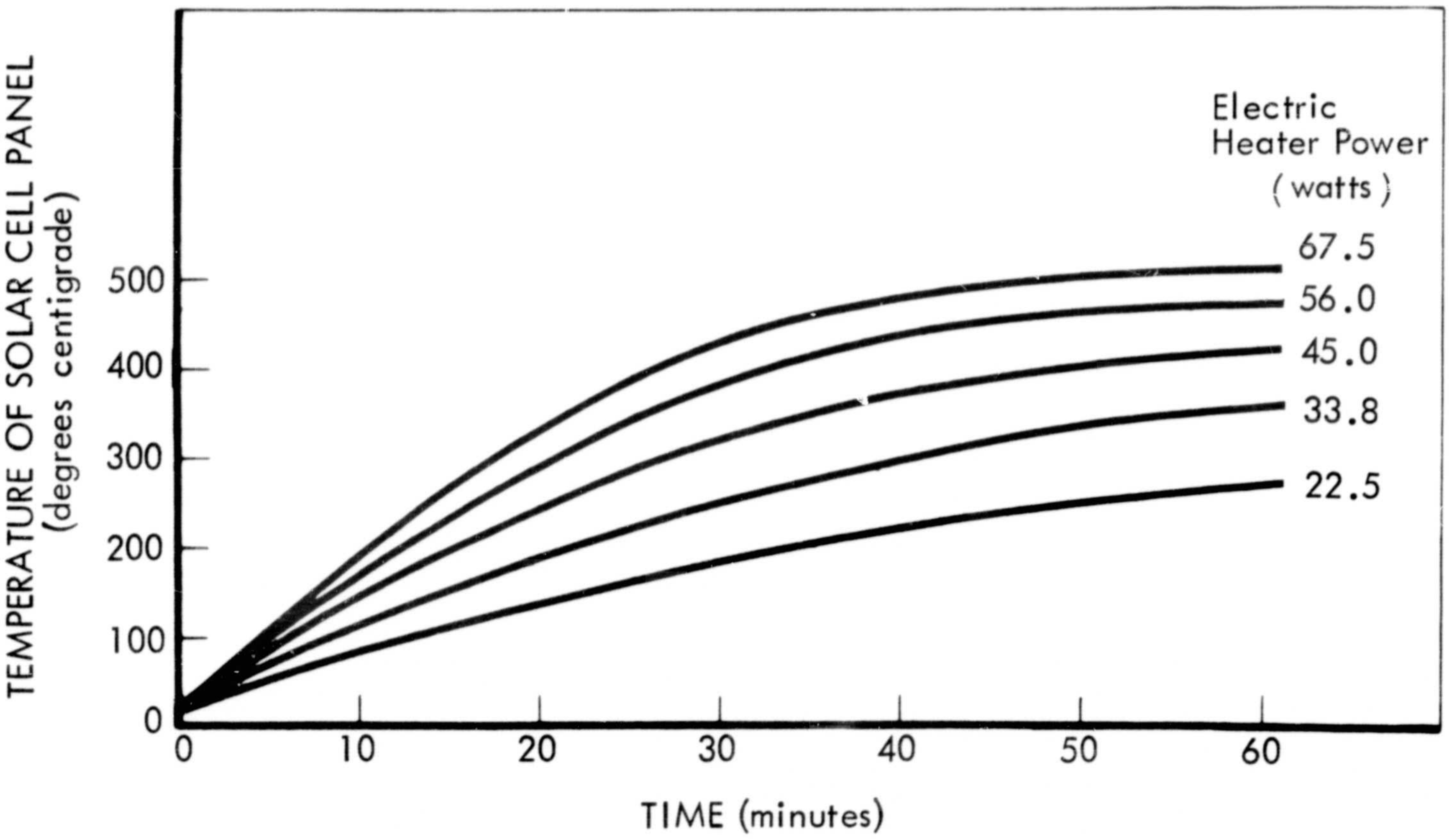

Figure 10: TIME-TEMPERATURE HISTORY OF PANEL WITH ALUMINUM INSULATION

Several approaches were suggested for the use of this coating. One is to coat the back of the substrate and then turn the solar panel over during thermal annealing. Insulation would be required over the solar-cell side of the panel during annealing. The drawback with this approach is that during normal solar-cell operation the back of the panel with its very low emittance would keep the cells hot.

A second approach is to use the black mirror on a sheet of aluminum foil in front of the solar panel. Analysis showed that a solar panel with a black-mirror coated aluminum shield on the Sun side and an aluminized H-film and fiberglass shield on the back side will reach 450°C within 1 hour. Figures 11A and B show the time-temperature history for various solar absorptances and thermal emittances.

Figure 11A shows that a black-mirror coating with a solar absorptance of above 0.90 and an emittance of 0.05 will heat the panel to 450°C within 1 hour. Coatings with absorptances of 0.80 and 0.85 will heat the panel to 450°C within 75 minutes. On the other hand. Figure 11B shows that if the thermal emittance is 0.10, then a coating with an absorptance of 0.95 will not heat the panel to 400°C in 75 minutes. The data show clearly that the thermal emittance of the coating must be carefully controlled to not exceed 0.05. The absorptance has a wider range of acceptable values, but the lowest practical absorptance is 0.90 unless longer times to reach annealing temperature can be tolerated.

As a result of the thermal analysis the black-mirror coating was selected for heating the solar panel to 450°C. Heater wires were placed in the panel to compensate for the differences between the thermal analysis and the test conditions.

TEST PANEL DESIGN

A 1-sq-ft panel incorporating high temperature technology was built. The substrate for this panel is 5-mil woven fiberglass cloth, supported around the edge with a Kovar-channel frame. Solar cells are cemented to the

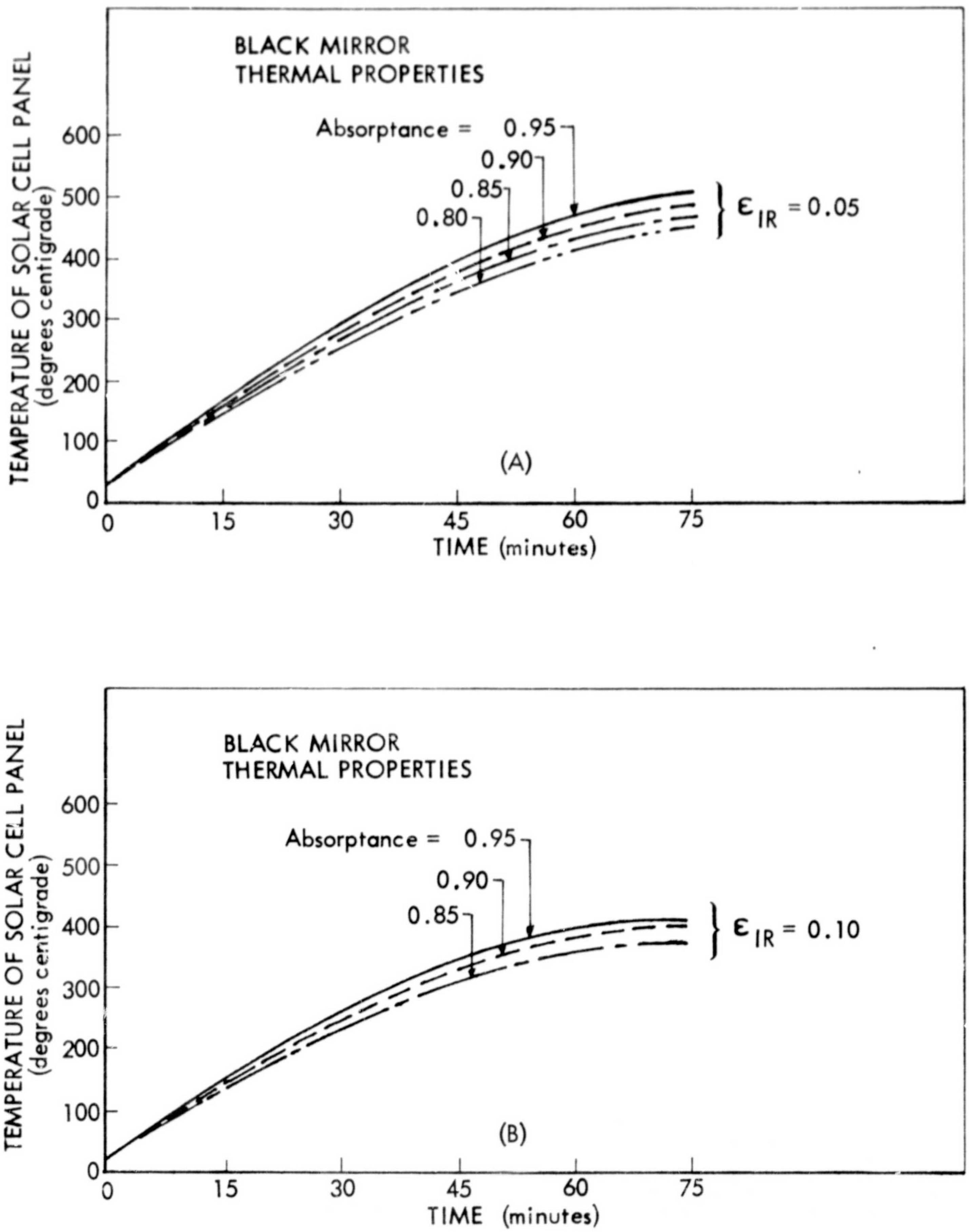

Figure 11: TIME-TEMPERATURE HISTORY FOR PANEL WITH BLACK MIRROR SHADE ON THE FRONT SIDE AND FOUR LAYERS OF ALUMINIZED INSULATION ON THE BACK SIDE.

substrate with Engelhard CA9R cement. Material selections were based on ability to retain strength at elevated temperatures and on coefficients of thermal expansion.

The CA9R adhesive was tested by bonding solar cells to a substrate of fiberglass. After curing was completed, the solar cells, adhesive, and substrate were cycled in vacuum eight times for 20 to 450°C. There was no deterioration in the adhesive and neither solar cells nor substrate was attacked chemically.

Other adhesives tested included the ceramic cements. These materials have a sodium silicate base, and at 450°C they attacked the fiberglass substrate, causing it to crumble. These cements were difficult to use, shrank during cure, and had poor adhesive strength. Dow Corning 92-024 silicone-rubber adhesive was tested to 450°C. The adhesive showed cracks after testing to 450°C when the pressure in the chamber exceeded 0.03 torr. Because it is marginal at 450°C it was decided not to use Dow Corning 92-024 adhesive.

The finished solar-cell panel (Figure 12) is composed of four modules, each module being 7 cells wide by 14 cells long. The solar cells are solderless n-on-p type with silver-titanium contacts and 1-mil integral covers. Copper wires connect the ends of the modules to stand-off ceramic terminals.

The system for heating the panel to 450°C in space consists of three major parts: a front shade; a rear insulating shade; and a motor for drawing the shades over the panel. The front shade was a black-mirror coating applied on one side of a 6-mil high-purity aluminum sheet, and a sulphuric-acid anodized coating on the other side. During heating, when the shade is drawn over the panel, the anodized aluminum surface reradiates heat to the solar cells. The black mirror, with an emittance of 0.04 in the infrared, will not reradiate heat back out into space. The shade that is drawn over the back of the panel has seven layers of 0.5-mil aluminized H-film separated by 1 mil of fiberglass cloth. This shade shields the back of the panel so that is will not radiate to space during heating.

Figure 12: HIGH-TEMPERATURE SOLAR-CELL PANEL

Electrical heaters in the adhesive between the solar cells and the fiberglass substrate supplement the solar heat collected by the black mirror. No attempt was made to minimize edge losses in the 1-sq-ft test panel.

During normal solar-panel operation the shades are stowed on the rollers at the base of the panel. For thermal annealing, a 400-Hz, 110-v.a.c. motor draws the shades over the panel. After thermal annealing the motor is reversed, and springs in the rollers retract the shades.

Two 400-Hz motors were procured and operated in a 0.025-torr vacuum for 1 hour. At the end of the test the motors were stopped and restarted to determine if the bearings would seize. No seizure occurred. One motor, made by Induction Motors Corp., is geared to run at 50 rpm. The other motor, made by Globe Industries, Inc., is geared to run at 4.0 rpm. The lower-speed motor appeared to be better suited for this particular application.

At the time of writing this report, the panel had been heated to 500°C using both the black mirror and the electrical heaters. No measurable degradation was observed in the solar cells.

NEW TECHNOLOGY

A thermal-diffusion bonding process has been developed for making bonds between the silver interconnector and the solar cell. The bonds have been tested, and the results of these tests are shown in the technical discussion.

In this new process, a silver interconnector is brought into contact with a solderless, silicon solar cell. A pressure of 56.2 kg/sq cm is applied to the joint as the assembly is heated to 400°C in vacuum, and then allowed to "soak" for 20 minutes. The resulting bond is a metal diffusion of silver itself. Bonds have withstood 10 thermal cycles from 20 to 500°C, and they should withstand temperatures up to the melting point of silver.

This process, which eliminates the need for solder and fluxes, appears adaptable to mass production.

This thermal-diffusion bonding process was used to assemble four modules, each having 98 solar cells. The modules were 7 cells wide by 14 cells long.

CONCLUSIONS AND RECOMMENDATIONS

From the work accomplished during this program, the following conclusions can be drawn.

1) Thermal-diffusion bonding can make an electrically and mechanically sound joint between a silver interconnector and a solderless silicon solar cell.

2) Thermal-diffusion bonding does not degrade solar-cell performance.

3) Joints properly formed by thermal-diffusion bonding are stronger than the silver-mesh interconnector.

4) A thermal-diffusion bonded joint can withstand 10 temperature cycles from 20 to 450°C and 10 temperature shocks from +100 to -190°C without degrading.

5) The solar-cell panel that was built can withstand 500°C in vacuum without deterioration.

Thermal-diffusion bonding appears to have many advantages beyond the high-temperature requirements of this contract. It eliminates the weight of solder, the contamination of fluxes, and the cleaning after joining, and allows the cells to experience high temperatures without interconnector joint failure. The process appears to be adaptable to mass production. It was not within the scope of this contract to fully investigate all the parameters of thermal-diffusion bonding to solar cells, but rather to develop the process to a point where it was suitable for fulfilling the contractual commitments. The work required to fully develop the process appears to be a research program in itself.

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